Pesticides and Chemical Fertilizers: Role in Soil Degradation, Groundwater Contamination, and Human Health

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Abbreviations

AOA	Ammonia-oxidizing archaea
AOB	Ammonia-oxidizing bacteria
CKD	Chronic kidney diseases
DDE	Dichlorodiphenyldichloroethylene
DDT	Dichloro-diphenyl-trichloroethane
EDC	Endocrine-disrupting chemicals
EM	Effective microorganism
ETL	Economic threshold level
F	Fungicides
FAO	Food and Agriculture Organization
FFS	Farmer field school
GHG	Greenhouse gas
H	Herbicides
HCH	Hexachlorocyclohexane
HYV	High-yielding varieties
I	Insecticides
ILO	International Labour Organization
IPM	Integrated pest management
IRM	Insecticide resistance management
N	Nitrogen
NGO	Nongovernmental organization
NPK	Nitrogen phosphorous potassium
OCPs	Organochlorine pesticides

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POPs	Persistent organic pesticides
SOC	Soil organic carbon
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCC	United Nations Framework Convention on Climate Change
USDA	US Department of Agriculture
USEPA	US Environmental Protection Agency
USGS	US Geological Survey
WHO	World Health Organization

1 Introduction

To ensure the food and nutritional security of the growing population with limited land resources, the use of fertilizers and pesticides in crop production is increasing at an alarming rate. A pesticide is a chemical or biological agent that kills, eliminates, or controls pests either alone or in a mixed form. Globally, a wide range of pesticides including insecticides, herbicides, weedicides, fungicides, and rodenticides have been developed to target specific pests in agriculture, horticulture, and residential settings (Van de Merwe et al. 2018; Jaffar et al. 2022). China (1,404,166 tons) had been reported as the largest consumer of pesticides in the world, followed by the United States (406,684 tons) and Brazil (221,582 tons), whereas pesticide exports from European nations were the highest in the world, followed by the United States, China, and Japan (FAO 2021; Singh et al. 2021). In 2019, India was the fifth largest exporter of agrochemicals, with pesticides valued at USD 3.4 billion. In 2020, India's exports amounted to USD 313.4 billion, representing around 10.9% of the country's GDP (Singh et al. 2021). Additionally, with the introduction of high-yielding varieties (HYV) during the mid-1960s, the country saw steep growth in the manufacturing and consumption of N fertilizers. As a result, India became the world's second largest producer and consumer of N fertilizers (Tewatia and Chanda 2017).

The world is experiencing rapid urbanization with the increase in population. By 2050, the global population will reach 9.7 billion, with the majority of this growth occurring in urban areas (World Population Prospects 2019; Salomon et al. 2020). An urban area comprises various agricultural/nonagricultural settings (Meftaul et al. 2020). Pesticides are often used in farming practices specific to cropping systems, but their uses in an urban context are broader and more diverse. This includes their application in gardens, lawns, golf courses, sealed areas, roads, wastewater treatment plants, etc. (Shamim et al. 2014; Stehle et al. 2019). Additionally, both homeowners and pest control experts use various pesticides to safeguard their furniture against insect damage, maintain sanitation, preserve esthetics, and reduce insect and disease threats (Meftaul et al. 2020; Srivastav 2020). Researchers had reported a comparatively higher concentration of persistent organic pesticides (POPs) in urban centers in developing countries such as Pakistan, India, and Nepal in Southern Asia (Nasir et al. 2014; Pokhrel et al. 2018). In 2016, US homeowners spent over USD 47.8 billion on lawn and garden products, with insecticides accounting for

roughly 80% of the total (Tran et al. 2020). Thus, in urban contexts, the reckless use of these chemicals is more prevalent, resulting in numerous accidents and exposures (Meftaul et al. 2020). Pesticides are frequently detected in residential runoff and surface waters and are likely to enter waterways following rainy events, mainly when applied to impervious surfaces such as driveways and pavements (Jiang et al. 2016; Van de Merwe et al. 2018). Extensive use of pesticides in household gardening is the primary cause of urban drinking water contamination, as polluted water percolates into the ground and contaminates groundwater, affecting human health when consumed (Khan et al. 2018; Syafrudin et al. 2021). Additionally, due to the constant release of pesticides into urban waters by wastewater treatment plants, aquatic creatures in urban waterways may be continuously exposed throughout the year (Shamim et al. 2014). One of the chief nonpoint sources of heavy metals in the upper Ganges is the extensive use of fertilizers (Prasad et al. 2020). Excess transportation of these nutrients into stagnant water has resulted in accelerated eutrophication (Khan et al. 2018). The overconsumption of dissolved oxygen by algae in aquatic environments kills the fish and other organisms, and the water becomes unusable for other purposes. The major health issues with exposure to pesticides are neuronal disorders, congenital abnormalities, fetal growth, and even cancers in humans (Asghar et al. 2016).

This book chapter discusses the adverse impacts of agrochemicals on the major components of the environment with a special reference to urban ecosystems. We also discuss the preventive and regulatory measures that can be taken by different stakeholders to safeguard the ecosystem from its hazardous effects.

2 Effects of Pesticides and Fertilizers on the Environment

2.1 Effects on Soil

Soil is the pivotal component of the earth's ecosystem. It provides water and nutrients to the plants and harbors the microorganisms that maintain the environmental quality. The following sections discuss the negative impacts of agrochemicals on soil health and soil microbial activities and biochemical reactions with reference to urban settings.

2.1.1 Soil Health

The term "soil health" refers to the soil's overall physical, chemical, and biological characteristics as they relate to crop production (Knight et al. 2013). Soil health is a subset of ecosystem health. Consistency in nutrient cycling, energy flow, stability, and resilience to stress are all representations of a well-fit ecosystem. Physical, chemical, and biological changes indicate soil health. Physical indicators include

texture, bulk density, porosity, field infiltrability, soil aggregate dynamics, water-holding capacity, and compaction. Chemical indicators include pH, salinity, sodicity, nutrient availability, and heavy metals. Biological indicators constitute organic matter content, active carbon, enzyme activity, C:N ratio, microflora and fauna, and soil respiration (Hubanks et al. 2018; Tripathi et al. 2020).

Urban soil is severely influenced by anthropogenic activities than natural soil (Meftaul et al. 2020). Urban soil exhibits high unpredictability, poor structure, and soil disturbances which affect the structural and functional characteristics such as porosity, bulk density, nutrient cycling systems, etc. (Attanayake et al. 2014; Igalavithana et al. 2017). Further addition of pesticides will inhibit soil microorganisms involved in the nutrient cycling of soils and have adverse effects on the soil health (Mandal et al. 2020).

2.1.1.1 Effects of Pesticides on Soil Health

Urban agriculture can enhance the sustainability and resilience of urban areas and contribute to a lower carbon economy by reducing the amount of fuel required to transport food at the city level; however, pesticide residues in soil, water, and air pose a risk to urban agriculture, particularly food safety (Ferreira et al. 2018; Meftaul et al. 2020). The long-term impact of pesticides on soil health depends on both soil and pesticide properties that influence the processes like sorption, biodegradation, chemical transformation, microbial transformation, volatilization, leaching, uptake by the organisms, etc. (Chiaia-Hernandez et al. 2017; Tudi et al. 2021). Properties that define the residency period of the pesticides, their fate, and the

Properties of pesticide that decide the residence time in the soil (Tripathi et al. 2020)	Factors affecting the fate of pesticides (Tripathi et al. 2020)	Factors influencing pesticides degradation (Singh 2012; Su et al. 2017; Tudi et al. 2021)
Chemical structure	Types of soil	Temperature
Volatility	Content of soil organic matter	pH
Water solubility	Hydrogen ion concentration	Soil moisture
Formulation	Half life period of pesticides	Intensity and exposure length of sunlight
Application	Diversity of soil microflora	Properties of pesticides

Fig. 1 Soil and pesticide properties that define the residency period, fate, and degradation of pesticide

degradation of pesticides are given in Fig. 1. On application, pesticides undergo various processes like degradation, transportation, sorption, and desorption (Okada et al. 2019; Liu et al. 2021). The longer these pesticides are found in their original form, the higher the chances of leaching into the soil (USEPA 2012). Pesticide concentrations showed an increasing trend as we move from suburbs to urban centers, and their concentrations increase with the increase in the age of the urban soil (Yang et al. 2012). Organochlorine pesticides such as aldrin, dieldrin, chlordane, p,p-dichlorodiphenyltrichloroethane, mirex, and toxaphene are categorized as persistent bioaccumulative and toxic chemicals by the US Environmental Protection Agency (USEPA). These chemicals are detrimental and affect the living systems due to their bioaccumulation within the food chain (Tripathi et al. 2020).

It was found that the residual effect of toxic pesticides changes with the initial application dosage (Tripathi et al. 2020). The application dose of pesticides determines the toxicity with more detrimental effects from higher doses than the lower. Thus, pesticides that persist in the soil for a long time are more harmful (Mandal et al. 2020). Application of lindane at a concentration of 156 and 125 g/ha inhibits microbial activities and crop growth. However, there were no changes in the crop yield when applied at a lower concentration (Glover-Amengor and Tetteh 2008).

2.1.1.2 Effects of Fertilizers on Soil Health

Overuse of agrochemicals is the main cause of the deterioration of soil health. The extent of the impact due to fertilizer on soil health and ecosystem function is controlled by their effects on primary productivity (Singh 2018; Tripathi et al. 2020). There are barely any direct toxic or lethal effects of excessive fertilizer use. The effects are slowly recognized in different soil processes and thus the productivity. Moreover, an optimum level of plant-accessible soil N and P is important for the proper functioning of the soil ecosystem. Variations in different soil properties like soil organic carbon (SOC), N, pH, availability of nutrients, and moisture content have been observed due to prolonged use of fertilizers (Wu et al. 2011). Before N fertilizers were introduced (in the mid-twentieth century), leguminous plants and organic matter were the main sources of N for crops (Singh 2018). The application of fertilizers increases the activity of soil microbes, which were otherwise limited by low concentrations of nutrients. However, continuous use of fertilizers causes soil acidification leading to the release of base cations (Ca, Mg, Al) from soil minerals, and the persistence of this situation for a prolonged time elicits nutrient disorder in plants (Tripathi et al. 2020). Moreover, soil acidification also interferes with the decomposition and mineralization of soil organic matter.

Rousk et al. (2009) had observed a fivefold decline in the growth of bacteria and fungi due to the lowering of pH from 8.3 to 4.0. In addition, soil acidification leads to nitrogen losses by NO_3, nitrogen leaching, and NO, N_2O, or N_2 emissions caused by nitrifiers and denitrifiers (Tang et al. 2016). Leaching of nitrate due to excessive use of fertilizers in the subsoil might result in pyrite oxidation, releasing sulfate and other trace elements. The application of fertilizers also adds heavy metals to the soil

and can be associated with their transportation to adjacent water bodies (Khan et al. 2018). Some radioactive matters like ^{238}U, ^{232}Th, ^{210}Po, and ^{40}K are found in phosphate fertilizers and heavy metals (Kara et al. 2004; Hassan et al. 2016).

2.1.2 Soil Microbial Activities and Biochemical Reactions

Soil is a divergent and suitable habitat for different microorganisms. Soil microorganisms are a vital component of agricultural and urban ecosystems as they actively enhance the fertility and productivity of the soil. Soil properties such as porosity, structure, aeration, and water infiltration are regulated by soil microflora by forming and stabilizing soil aggregates (Srivastava et al. 2016). Functions of soil microflora include nutrient cycling, biocontrol of soilborne phytopathogens, organic matter decomposition, nutrient supply, detoxification of contaminated soil, and other plant growth functions such as phytohormone production (Prashar and Shah 2016; Tripathi et al. 2020).

Pesticides are frequently sprayed on urban soils in order to maintain idyllic urban green zones and lessen damage from insects and weeds (Nugent and Allison 2022). Due to the long persistent nature of agrochemicals, they affect the soil microorganisms and, thereby, the soil health (Prashar and Shah 2016). Incorporating agrochemicals affects the beneficial soil microorganisms involved in vital enzymatic components and synchronizing important chemical processes in soil (Malik et al. 2017). Thus, on the removal of beneficial nontarget soil microbes, they have a detrimental effect on nutrient cycling and retention, soil's nutrient pool, and soil fertility (Hashimi et al. 2020).

2.1.2.1 Effects of Pesticides on Soil Microbial Activity and Biochemical Reactions

Soil microorganisms' response to a range of chemical pesticides varies and depends on the nature of pesticides, microorganisms in the soil, and soil properties. In addition, toxicity potential and pesticide application change the structural and functional diversity of soil microbes (Prashar and Shah 2016). Table 1 shows the effects of pesticides on soil microbes. The utilization of agrochemicals continues to alter the diversity and structure of beneficial plant rhizobacteria in agricultural systems (Malik et al. 2017). Leguminous crops fix 100–200 kg N per hectare per year. Herbicides' application has the highest detrimental impact on symbiotic nitrogen fixation compared to all other potential unfavorable effects (Burul et al. 2022). With the elevated use of pesticides, changes in microbial biomass, genetic diversity, and catabolic activities were observed (Wang et al. 2008; Sumalan et al. 2010). Many researchers had reported the pesticide impacts on soil enzyme activities (Table 2). These include hydrolases, nitrate reductase, urease, oxidoreductases, nitrogenase, and dehydrogenase activities. Furthermore, the impacts of pesticides are seen in the biological nitrogen fixation along with their biotransformation processes

Table 1 Effects of pesticides on soil microbes

Pesticide name (type)	Effects on soil microbes	References
Chlorpyrifos (I)	Colony-forming units of bacteria and fungi number decrease	Supreeth et al. (2016)
Cypermethrin (I)	Microbial diversity decreases with an increased dose of insecticide	Tejada et al. (2015)
Imidacloprid (I)	With increased dose of insecticide, number of bacteria decreased	Cycoń and Piotrowska-Seget (2015)
Triazole (F)	Capability to inhibit the proliferation and metabolism of beneficial bacteria and their associated transformation of soil nutrients through cell wall lysis	Satapute et al. (2019)
	Strongly affects the structure of the microbial communities in soil and usually decreases the soil microbial population	Roman et al. (2021)
Glyphosate (H)	The presence of glyphosate reduced the population of bacteria, microbial biomass, and acidobacteria	AL-Ani et al. (2019)
Malathion (I)	Malathion-treated soil samples had the lowest microbiological activity and counts of bacteria, fungi, and actinomycetes	AL-Ani et al. (2019)
Fluoxastrobin (F)	As per the average well color development (AWCD) tests, the soil microbial diversity was found to be influenced, i.e., it inhibited microbial strains	Zhang et al. (2019)
Boscalid (F)	Multiple boscalid treatments decreased soil microbial diversity and network complexity, disrupted soil microbial community, and inhibited soil microbial function	Han et al. (2022)
Mesotrione (H)	Soil microbial community structure and microbial diversity declined after mesotrione exposure Bacteria, fungi, and actinomycetes were all present in lower quantity in the soil treated with mesotrione at 1.0 and 5.0 mg/kg.	Du et al. (2018)
Bromoxynil (H)	Bacterial population decreased by 30%, actinomycetes population decreased by 23.4%, and fungus population decreased by 34%	Abbas et al. (2015)

H herbicides, *F* fungicides, *I* insecticides

(ammonification, nitrification, denitrification, phosphorus solubilization, and S-oxidation) (Monkiedje and Spiteller 2005).

2.1.2.2 Effects of Fertilizers on Soil Microbes

Long-term fertilization has a substantial effect on the soil microorganisms and their extracellular enzyme activity in urban agricultural soils (Igalavithana et al. 2017). Inorganic fertilizers can increase nutrient availability in the soil. However, inappropriate and excessive use of fertilizers does not always result in increased crop yield

Table 2 Effects of pesticides on soil enzymes

Pesticide (types)	Effects on soil enzymes	References
Mesotrione (H)	Decrease the soil dehydrogenase activity with increased herbicide doses	Pose-Juan et al. (2015)
Triazole (F)	Facilitate changes in the activity of soil enzymes and negatively affect the biochemical activity and can impair soil fertility and productivity	Satapute et al. (2019)
	Strongly affects the activity of enzymes present in the soil	Roman et al. (2021)
2,4-Dichlorophenoxyacetic acid (H)	Application of 2,4-D caused the greatest decline in soil dehydrogenase activity	Arora et al. (2019)
Fluoxastrobin (F)	Enzymatic activities such as β-glucosidase, dehydrogenase, and urease were significantly lower on the application of pesticide dose in the samples than those of the controls	Zhang et al. (2019)
Mesotrione (H)	Mesotrione (5.0 mg/kg) treatment resulted in a decrease in β-glucosidase activity	Du et al. (2018)
Bromoxynil (H)	With the application of bromoxynil herbicide at 2250 ml/ha, urease activity decreased by 30%, dehydrogenase activity was inhibited by 36%, and alkaline phosphatase activity decreased by 34%	Abbas et al. (2015)
Azoxystrobin (F)	Dehydrogenase activity is the most sensitive to azoxystrobin Urease activity was initially inhibited by azoxystrobin; however, the inhibitory effect faded off and recovered to the level of control in the end	Wang et al. (2018)
Chlorpyrifos (in presence of earthworms) (I)	Inhibits cholinesterase and carboxylesterase activities of earthworm strongly	Sanchez-Hernandez et al. (2018)
Cypermethrin (I)	With increased dose, arylsulfatase soil dehydrogenase, urease, phosphatase, and β-glucosidase activities decrease	Tejada et al. (2015)
Linuron (H)	Linuron in 100-fold dose decreases dehydrogenase activity of the soil	Medo et al. (2021)
Dimethachlor (H)	Dimethachlor in 100-fold dose decreases soil enzymatic activities	Medo et al. (2021)
Triticonazole (F)	Barley and wheat seeds treated with various dosages of triticonazole were sown in chernozem soil, and the activities of dehydrogenase and phosphatase decreased, whereas urease activity increased	Roman et al. (2022)

H herbicides, *F* fungicides, *I* insecticides

and can cause environmental problems in agroecosystems (Wimalawansa and Wimalawansa 2014a; Yousaf et al. 2017). Proton release to the soil by N cycling and the acidic reaction of soluble P fertilizers resulted in soil acidification (Guo et al. 2010; Van der Bom et al. 2018). Again, soil pH, along with SOC and N, is an

important driver of microbial community change, whereas P plays a minor role (Hartmann et al. 2015; Francioli et al. 2016). Long-term input of ammonium-N-containing fertilizers decreases soil pH and influences the biomass, structure, microbial diversity, and activity of soil microbial communities (Geisseler and Scow 2014; Francioli et al. 2016). Zhou et al. (2015) had also reported similar observations on the application of inorganic fertilizers for 44 years. In contrast, NPK combined with organic manure increases microbial biodiversity and bacterial population (Sun et al. 2015).

A change in fertilization pattern (inorganic/organic fertilizer) did not change the composition and richness of ammonia-oxidizing archaea (AOA) but altered the ammonia-oxidizing bacteria (AOB) in calcareous and neutral soils exposed to N fertilizer (Shen et al. 2008, 2011). However, different responses to organic and inorganic fertilizers had been reported by Zhou et al. (2015). Adding inorganic fertilizers increases AOB, whereas AOA increases under the influence of organic N fertilizers. Additionally, after 23 years of fertilization, using chemical fertilizers with or without organic manure can alter the richness and composition of AOA and AOB in neutral soil (Xue et al. 2016). Thus, excessive and unjustifiable use of synthetic fertilizers and pesticides has led to massive soil contamination, which has negatively impacted the soil biodiversity. Similarly, pesticide poisoning in the water system especially groundwater is another well-known and widespread global problem. The following sections discuss the effects on the urban water system.

2.2 Effects on the Urban Water System

Pesticides used in urban areas pose a risk to surface water systems since impervious pavement increases runoff, which can result in severe contamination and aquatic toxicity (Cryder et al. 2019). Jiang et al. (2016) had reported that hydrophobic pesticides such as pyrethroids and fipronil can bind to loosen particles of impervious substances. These particles prove to be an important source of pesticide contamination in the runoff in urban settings. Global urban land area is projected to increase tremendously during the year 2000–2030 due to urbanization, which will aggravate urban pesticide runoff and surface contamination (Cryder et al. 2019). In addition, pesticides related to turf grass management were detected in storm runoff and surface water of urban watersheds (Rice et al. 2017). The extent to which pesticides contaminate surface waters is influenced by physicochemical characteristics such as retention by soil components, degradation rate, water solubility, and properties of the medium in which the compounds are applied and degraded (Barra Caracciolo et al. 2009; Khatri and Tyagi 2015).

Groundwater has been considered as a pure and reliable form of drinking water for a long time. Pesticide contamination of groundwater is a huge concern since the majority of water requirement is fulfilled by groundwater in most part of the world (Khatri and Tyagi 2015; Malyan et al. 2019). Thus, a detailed understanding of the various urban sources of pesticide pollution, their entry points, and their dynamic

contributions to the urban environment is required for the implementation of appropriate strategies to mitigate these dangers (Meftaul et al. 2020). The poisoning of groundwater by agrochemicals and its ecological consequences are addressed in the following sections.

2.2.1 Contamination of Groundwater by Agrochemicals

The primary way by which pesticides reach the groundwater is due to their ability to penetrate the soil and make their way through the unsaturated region to the water table. They also reach the groundwater by leaching or percolating processes (Malyan et al. 2019). The transportation of pesticides in groundwater is different from that of streams (surface water). Water-soluble pesticides can travel large distances in groundwater. Numerous variables affect the transportation method (Table 3).

Groundwater contamination is a significant concern in areas where groundwater aquifers are the primary source of drinking water. Contaminated groundwater, when resurfaced, affects nontargeted organisms, including endangered species (Agarwal et al. 2010). Figure 2 shows the movement of pesticides through the environment. As reported by the US Geological Survey (USGS), groundwater contained no less than 143 pesticides and 21 transformation products. These include pesticides from every significant chemical class (USGS 2014). In the last few years, several cases of groundwater pollution due to pesticide residues had been reported all across the world. For example, Somashekar et al. (2015) had reported methyl isocyanate in water samples obtained from the city of Mysore in the Indian state of Karnataka. Herbicides such as diuron, dibromochloropropane, bromacil, simazine, and others were found in groundwater of the San Joaquin Valley, California, at concentrations that are harmful to the ecology and human health (Troiano et al. 2013). Given the above evidence, it is crucial to develop effective ways to make proper strategies that would prevent the flow of excessive agrochemicals to groundwater.

2.2.2 Ecological Implications of Agrochemical Contamination in Groundwater

Numerous detrimental alterations caused by pesticide pollution are prevalent in urban aquatic ecosystems (Meftaul et al. 2020). Due to its persistency and stability in the environment, it results in biomagnification and bioaccumulation in living organisms once it enters the food chain. The disproportionate use of nitrogenous fertilizers is the main reason for the high nitrate content in groundwater. A variety of health diseases are caused by drinking nitrate-contaminated water. Pesticides also affect the groundwater microbial system. The relevance of groundwater microorganisms is acknowledged because they provide ecosystem services such as drinkable water, nutrient cycling, and toxin degradation (Jacobsen and Hjelmso 2014). Other implications due to the application of agrochemicals (pesticides and

Table 3 Factors affecting the possibility of pesticides reaching groundwater

Factors	Properties	Reasons	References
Pesticide properties	Solubility	The higher the solubility of pesticides, the greater potential to leach down to the groundwater	Trautmann et al. (1989); Damalas and Eleftherohorinos (2011)
	Adsorption	Pesticide with strong adsorbing capacity is unlikely to reach the groundwater irrespective of its solubility	
	Degradation	Pesticide degradation includes processes like photolysis, hydrolysis, and oxidation	
	Volatility	Higher vapor pressure is subjected to faster vaporization of pesticide to the atmosphere, making it less available to leach down	
Soil properties	Organic matter	Soil organic matter affects the adsorption of pesticides to the soil	Trautmann et al. (1989); Damalas and Eleftherohorinos (2011)
	Soil texture	Movement of the water along with the dissolved chemical pesticides through the soil is affected by "soil texture." The coarser the soil texture, the greater the chance of pesticide leaching down	
	Soil permeability	Proper timing and well-designed application methods minimize leaching to groundwater in highly permeable soil	
	Soil structure	Aggregation of soil particles affects the movement of water. Loosely packed soil is more likely to allow dissolved pesticides to easily percolate down	
Site conditions	Depth to groundwater	Shallow depths of groundwater; degradation and adsorption opportunities are low along with filtering action provided by soil	Trautmann et al. (1989)
	Topography	Rate of infiltration is higher than runoff in flat or depressed areas, which enhances the vulnerability to leaching	
	Climate	Climatic conditions like rainfall affect the transport process. Areas with high rainfall are susceptible to leaching of pesticides	
	Geologic conditions	Areas with quick permeability of geologic layers are vulnerable to groundwater quality	
Management practices	Pesticide application method, application rate, time of application	The way of pesticide application affects the leaching potential. High amount of pesticides used in proximity to a heavy rainfall or irrigation makes it more likely to leach down to groundwater	Trautmann et al. (1989); Ramsay et al. (1991); Arias-Estévez et al. (2008)

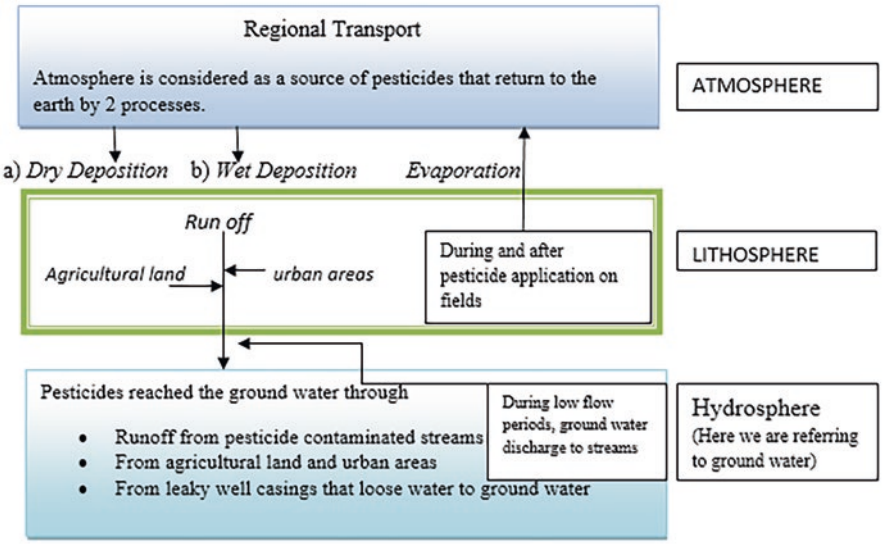
Regional Transport
Atmosphere is considered as a source of pesticides that return to the earth by 2 processes.
ATMOSPHERE
a) Dry Deposition
b) Wet Deposition
Evaporation
Run off
Agricultural land
urban areas
During and after pesticide application on fields
LITHOSPHERE
Pesticides reached the ground water through
Runoff from pesticide contaminated streams
From agricultural land and urban areas
From leaky well casings that loose water to ground water
During low flow periods, ground water discharge to streams
Hydrosphere
(Here we are referring to ground water)

Fig. 2 Pesticide movement in the environment (air, land, and groundwater) (based on/adapted from Majewski and Capel 1995; Gilliom et al. 2006)

fertilizers) include its impacts on crop health and human health (Srivastav 2020; Dhuldhaj et al. 2022).

The above sections have discussed the contamination of groundwater by agrochemicals. Urban population is more affected due to high population density, different land use pattern, and presence of impervious structures. The effect of pesticides on human health has been discussed in the following sections.

2.3 Effects on Human Health

The widespread use of organochlorine pesticides (OCPs) to increase agricultural production and to prevent vector-borne diseases such as malaria, dengue, and leishmaniasis, particularly in urban areas, had created a significant threat to human health (Guida et al. 2021; Ashesh et al. 2022). Lack of knowledge on pesticide handling, improper storage and disposal, use of cheaper but toxic pesticides, and lack of enforcement and regulatory systems are some of the factors identified that worsen the health hazards (Nath and Deka 2022). In developing countries, urban areas were found to be at greater risk than semi-urban or rural agricultural areas (Anand et al. 2021). For example, Sharma et al. (2014) had reported a higher concentration of OCPs in urban areas of Punjab. Muller et al. (2017) had reported a higher amount of PCB congeners in human milk of urban areas compared to rural

areas of northern Tanzania. The enhanced toxicity in the urban environment is caused by the additives or carrier elements of pesticides (Castro et al. 2014). Richards et al. (2016) had found the prevalence of pyrethroids in the dust particles on the paved surfaces of individual houses in urban environments and found them to be uniformly distributed in the areas adjacent to each residence, indicating significant redistribution. The route of exposure includes oral, dermal, respiratory tract, and ocular exposure (Meftaul et al. 2020). There are limited research works on the effects of pesticides in typical urban environments, even though ten times larger dosages of different pesticides are applied simultaneously to control a variety of pests and to maintain urban lawns and golf courses (Ali et al. 2014; Bekken et al. 2021). This poses a risk for children and individuals who spend a significant time of the day in playing and recreational activities in those areas.

2.3.1 Acute Health Effects of Pesticides

Acute health effects are adverse effects that occur immediately or within a short span of time after the exposure to pesticides. Human exposure to these pesticides might lead to acute health effects such as fatigue, dizziness, nausea, headache, body aches, skin rashes, skin discomfort, excessive sweating, vomiting, impaired vision, tremors, panic attacks, and cramps (Kumari and Reddy 2013; Suryawanshi and Patil 2016; Nath and Deka 2022; Dhuldhaj et al. 2022). Organophosphate is the most common toxic agent for acute poisoning (Chowdhury et al. 2011). Delayed polyneuropathy, cholinergic syndrome, intermediate syndrome, and chronic organophosphate-induced neuropsychiatric illness are the four main neurotoxic effects of organophosphate pesticides in people (Jokanović 2018). Malathion, parathion, and carbamates are common organophosphates that cause interruption of impulse transmission at the synaptic level and act as acetylcholine esterase (AchE) inhibitors. ACh accumulation results in the over-activation of neurons affecting muscles (Dixit et al. 2021). Similarly, OCPs are typically characterized as chemicals that are bioaccumulative and persistent and are suitable for long-distance transportation (Taiwo 2019). Organochlorines such as DDT (dichloro diphenyl trichloroethane) and endosulfan are potent pesticides. Endosulfan is a debatable agrochemical due to its acute toxicity, bioaccumulation potential, and endocrine disruptor activity (Lozowicka et al. 2015). Herbicides also affect the nervous and excretory systems (Casida 2009; Singh et al. 2016).

2.3.2 Chronic Health Effects of Pesticides

Pesticides used for an extended time, even a relatively small amount, can induce chronic sickness in humans. Some of the major chronic illnesses caused by chronic exposure to pesticides are discussed below.

2.3.2.1 Neurotoxicity

Pesticides that target the neurological system include organochlorines, organophosphates, and carbamates (Dixit et al. 2021). Neurological effects such as memory loss, impaired visual ability, coordination loss, altered or uncontrollable mood and general behavior, decreased motor abilities, and neurodevelopmental impacts were reported from pesticide poisoning (London et al. 2012; Biswas et al. 2014; de Joode et al. 2016). Prolonged exposure to low or high levels of pesticides during adulthood, childhood, or pregnancy (utero-exposure) causes nervous disorders like Parkinson's disease and Alzheimer's disease. Organophosphate and organochlorine pesticides affect synaptic junctions in the nervous system by regulating acetylcholinesterase, which may lead to Alzheimer's disease when exposed later in life (Hayden et al. 2010). The substantia nigra, a basal neuron in the brain, cannot produce dopamine causing Parkinson's disease. Qi et al. (2014) suggested that herbicides like rotenone and paraquat disrupt this neuron and inhibit dopamine production, leading to Parkinson's disease.

2.3.2.2 Reproductive Health

Exposure of pesticides to women of reproductive age has several consequences, such as infertility disorders due to their effects on the hormones or follicle count (Rani et al. 2021). Exposure to pesticides during pregnancy might lead to premature or spontaneous abortions, incessant stillbirth, neurodevelopment alterations in the child, etc. (Neghab et al. 2014; Chilipweli et al. 2021; Rani et al. 2021). Anand et al. (2021) and Sharma et al. (2020) had reported the presence of organochlorine, pyrethroids, and DDT and DDE (dichlorodiphenyldichloroethylene) in the breast milk of mothers in semi-urban and urban areas of Kolkata and northwestern parts of the Himalayas in India, respectively. Sharma et al. (2014) had also reported higher intake of DDT and HCH (hexachlorocyclohexane) by infants than the recommended values in some of the samples. Exposure to pesticides affects male fertility in terms of semen quality, DNA fragmentation, and chromosome aneuploidy (Giulioni et al. 2022). Researchers had reported that mothers with higher pesticide metabolites in their breast milk have children (boys) having cryptorchidism (Damgaard et al. 2006; Desalegn 2022).

2.3.2.3 Cancer

Several studies have shown strong evidence between pesticide exposure and cancer occurrences. Pesticide application on a significant commercial level or at home highly increases the risk of leukemia, thyroid (Alavanja et al. 2013), kidney (Xie et al. 2016), lung, and pancreatic cancer (Shankar et al. 2019; Porta et al. 2022). Kumar et al. (2022) and Wan et al. (2022) had reported that exposure to

xeno-estrogenic pesticides results in elevated breast cancer risk. Similarly, Kabir et al. (2018) had reported a positive correlation between pesticide exposure and prostate cancer death. Child leukemia was positively correlated with exposures to unidentified household pesticides, insecticides, and herbicides during pregnancy (Kim et al. 2017). Studies had also reported that exposure to pesticides during pregnancy may contribute to acute leukemia in children under 2 years of age (Ferreira et al. 2013).

2.3.2.4 Other Health Effects of Pesticides

Pesticide exposure could lead to hypothyroidism in women at childbearing age and menstrual irregularities (Suhartono et al. 2018; Abdel-Rasoul et al. 2019). Additionally, pesticides might harm the respiratory system and cause dry cough, wheezing, bloody sputum, and respiratory system irritation (Fareed et al. 2013). Buralli et al. (2018) had reported the danger of lung disorders, increased mortality, and morbidity rates in those exposed to pesticides. Furthermore, endocrine-disrupting chemicals (EDC) like DDE, a major metabolite of insecticide DDT (Cano-Sancho et al. 2017), could be involved in causing diabetes (Ruiz et al. 2018). Moreover, the size of B-islet cells decreased, and blood glucose and calcium level stimulation increased during the preparation of imazamox-based herbicides (Sevim et al. 2019). Guzzardi et al. (2016) conducted a study to explore the relationship between organochlorine pesticides and aging. They had reported that telomere length was affected by oxychlordane and TNC Biological Fungicide pesticides, which may lead to accelerated aging.

2.3.3 Effects of Fertilizers on Human Health

Higher than the suggested level of fertilizers like phosphate pollutes the water bodies and makes them unsafe for human use. This causes chronic kidney diseases (CKD) (Wimalawansa and Wimalawansa 2014a). Excessive nutrients in a water body (eutrophication) alter the water's natural vegetation, change the color, and render it unfit for human consumption. Likewise, excessive use of fertilizers results in contamination of groundwater with nitrate. Human exposure to nitrate results in the immobilization of hemoglobin in the blood due to nitrate-concentrated water, causing methemoglobinemia (Sharma and Singhvi 2017). High nitrates in drinking water had been reported to cause disorders like hypertension (Kumari and Rai 2020), non-Hodgkin's lymphoma (Poh et al. 2022), thyroid cancer (Bivolarska and Gatseva 2015), and enhanced infant mortality (Ashraf et al. 2019). Carcinogenic compounds form a nitrosation reaction in the stomach when other organic compounds react with nitrate compounds. These carcinogenic nitroso compounds are thought to be the origin of some forms of cancers in humans (Ashraf et al. 2019).

It is clear from the above discussion that society needs proper implementation of strict reforms and laws to reduce the effects of pesticides on human health and the

environment. More innovative agricultural practices and sustainable approaches of pest control could be a significant step in safeguarding the environment. Preventive measures for agrochemicals are discussed below.

3 Preventive Measures of Agrochemical Pollutants

Agrochemical pollution is one of the severe threats to the environment in the present-day scenario. Excessive use of these agrochemicals adversely affects water bodies, soil, and health. Therefore, farmer communities directly exposed to these chemicals face profound health implications (Tripathi et al. 2020; Dhuldhaj et al. 2022). The leading causes of pesticide contamination include ignorance of the adverse effects, irresponsible behavior on the part of farmers and agrochemical sellers, and substantial government fertilizer subsidies (Wimalawansa and Wimalawansa 2014a). Due to the persistent nature of these agrochemicals in the environment, more stringent laws and policies must govern their preventive measures.

3.1 Organic Farming and Integrated Pest Management System

The Food and Agriculture Organization (FAO) and World Health Organization (WHO) have defined organic agriculture as "Organic agriculture is a holistic production management system which promotes and enhances agro-ecosystem health, including biodiversity, biological cycles, and soil biological activity. Furthermore, it emphasizes the use of management practices in preference to using off-farm inputs, considering that regional conditions require locally adapted systems. This is accomplished by using, where possible, agronomic, biological, and mechanical methods, as opposed to using synthetic materials, to fulfill any specific function within the system." Nowadays, farmers who have adopted organic practices are familiar with modern equipment, knowledge of resistant crop varieties, soil and water conservation practices, and modern techniques related to livestock (Reganold and Wachter 2016).

The organic farming practice is known for its sustainable production with minimum environmental impacts and high-quality food without residues of agrochemicals. In addition, research indicates that under extreme drought conditions, organically managed farms are more productive than their conventional equivalents. This could be attributed to greater water-holding ability of organically farmed soil (Siegrist et al. 1998; Lotter et al. 2003). This property will help to cope with the severe drought conditions in recent years. In addition, crop rotations, the growth of leguminous plants to provide nitrogen to the farmed soil, fewer external nutrient inputs, and a rejection of mineral fertilizers and synthetic chemicals are other vital components of organic farming compared to conventional agriculture. Organic

practices control the soil organic carbon (SOC) content through soil carbon sequestration (Leifeld and Fuhrer 2010).

According to the United Nations Framework Convention on Climate Change (UNFCC 2008), the process of soil carbon sequestration can counterbalance large proportions of methane and nitrous oxide released from agricultural fields. Many international reports have recognized organic agriculture as a highly demanding and innovative farming system, which helps balance multiple sustainability goals and eventually plays a vital role in global food and ecosystem security (Food and Agriculture Organization of the United Nations; The National Academies 2012). In addition, studies have revealed that organic farming is more energy efficient than conventional agrochemical practices (Tuomisto et al. 2012; Lee et al. 2015).

In India, Sikkim officially adopted a resolution to switch to organic farming in India in 2003. Now, Sikkim is the first state in the world that is 100% organic (Sikkim State Policy on Organic Farming, India 2004). In recent years, Sikkim has evolved as a major exporter of organic fruits, flowers, spices, and vegetables. After the adoption of organic practices, the state has turned its economic conditions more uplifted. Similarly, Sri Lanka, a developing nation, has enhanced productivity and decreased environmental contamination by implementing ancient agricultural practices, such as using animal manure and compost in the fields, relying on cascade tanks, and using modern methods (Wimalawansa and Wimalawansa 2014b).

3.1.1 Integrated Pest Management (IPM)

Integrated pest management (IPM) is another tool to minimize the harmful impacts of synthetic chemicals on the environment without compromising crop production. According to FAO (2020) and the US Department of Agriculture (USDA) (2018), IPM is an inclusive program that incorporates various other techniques such as cultural, biological, physical, and chemical controls and minimizes environmental and human health risks. Adopting IPM in urban, agricultural, and wildland or natural areas can manage all kinds of pests and prevent long-term damage by managing the ecosystem. Usually, in IPM, the use of chemical pesticides is the last resort to manage the pest population below the economic threshold level (ETL). Therefore, pesticide use should be judicious so that no associated problems would exist.

For the last three to four decades, both developed and developing countries have adopted the IPM techniques in agricultural fields, which tremendously reduced the use of agrochemicals (Peshin and Zhang 2014). For instance, the USEPA (2011) estimated that during 2006–2007, the use of organophosphate insecticides declined by approximately 63%, i.e., from 40 million kilograms in 2000 to 15 million kilograms in 2007. Furthermore, studies have shown that Italy reduced pesticide use in agriculture and horticulture by 56%, followed by the United Kingdom and France (44%) (Peshin and Zhang 2014). By following IPM practices, India has reduced dependency on pesticides in cash crops like cotton, rice, and vegetables. The Directorate of Plant Protection Quarantine and Storage, Ministry of Agriculture and Cooperation, Government of India, shows the impact of IPM programs

implemented since 1985. The following indicates that IPM has reduced the need for pesticides: Rice and cotton production increased in IPM fields from 6.74% to 40.14% and 22.70% to 26.63%, respectively. The spraying of chemical pesticides decreased from 50% to 100% in rice and from 29.96% to 50.50% in cotton. Biopesticide usage increased from 123 MT in 1994–1995 to 7804 MT (Tech Grade) in 2019–2020, and total chemical pesticide consumption decreased from 61,357 MT (Tech Grade) in 1994–995 to 60,599 MT (Tech Grade) during 2019–2020.

Within the IPM, insecticides are considered as an essential part. In urban ecosystems (e.g., agricultural systems and situations), pesticides are often a convenient, economical, and fast-acting method of crisis management. As part of IPM, insecticide resistance management (IRM) strategies are undertaken in urban ecosystems (Zhu et al. 2016). IRM strategies include the state and mechanisms of insecticide resistance, overcoming or delaying resistance to current chemicals, and preventing the development of resistance to new pesticides by reducing insecticide selection pressure (Denholm and Rowlan 1992; Georghiou 1994). Recent development in green practices in agricultural industries is bringing positive changes to the economy. In India, the agrochemical industry is gradually adopting more environment friendly practices. Companies have adopted implementing zero discharge solutions, which has yielded considerable benefits. Many companies have developed several green biopesticides, biofertilizers, and biostimulants. Various new technologies have been developed and adopted in urban and rural agricultural practices to prevent pollution from the agrochemical. Among these, formulations with nanoparticles, the use of drones for spray, improved nozzles, electrically charged liquids, and high-performance adhesives that enhance retention, lowering the use of agrochemicals, are some of the prominent technologies. These technologies improve productivity, reduce costs, and keep the environment safe (Alawadhi 2022).

3.2 Training Programs and Workshops for Raising Awareness

Studies have revealed that little knowledge on proper utilization and management of agrochemicals, careless handling, and lack of information and training are among the factors leading to pollution of the environment and adverse health risk to farmers (Recena et al. 2006; Polidoro et al. 2008). Therefore, it is crucial to engage every grower in some training program or awareness program. Community participation is the key to the success of IPM and organic farming practices. The USEPA (2022) has recognized that for implementing IPM, awareness, education, and outreach programs are the key facilitators. Adequate training and technical support are essential for IPM to be successful in implementation (Parsa et al. 2014).

International bodies like the International Labour Organization (ILO), Food and Agricultural Organization (FAO), and World Health Organization (WHO) have provided various guiding rules and regulations for the use of agrochemicals in different developed and developing countries. On the other hand, the FAO Asian Regional IPM/Pesticide Risk Reduction Programme has conducted many farmers' education

programs and participatory research activities. They promote and support IPM in vegetables by Asian smallholder farmers in collaboration with government and non-governmental organizations. This kind of training approach by the FAO Regional IPM Programme is primarily known as the farmer field school (FFS).

Three types of human resource development programs have been implemented in India under the National Policy on Integrated Pest Management. They are as follows:

- Farmer field school program
- Season-long training program
- Short-duration training programs on IPM

Farmers' participation in various workshops and training programs depends on how they get motivated by the same objectives. For example, through various non-governmental organization (NGO) campaigns, farmers can be motivated and requested by consumers' positive aspects, such as demand for pesticide-free products. However, studies have revealed that the primary source of information for the farmers is their fellow men and extension advisors (Farooq et al. 2007). Furthermore, the seller or dealer is the source of popularity for a particular agrochemical in a rural community. Therefore, it is essential to introduce various information programs frequently through mass media like TV and radio talks and training programs about precautionary measures and hazardous effects of pesticide overuse directly to the farmers.

3.3 Role of Government in Strengthening the Laws and Policies

Governments are the key controller of the unregulated and indiscriminate use of agrochemicals by strengthening the prevailing laws and policies. Various international partnership programs have been adopted in recent years to support IPM programs. For example, the "Global IPM Facility" program, cosponsored by the Food and Agriculture Organization of the United Nations (FAO), the World Bank, the United Nations Development Program (UNDP), and the United Nations Environment Program (UNEP), has been in operation since 1995 (Kelly 2005). To abate agrochemical pollution, the government must take appropriate initiatives regarding strict laws and policies. Furthermore, depending on the toxicity and hazardous nature of the agrochemicals, policies and regulations have to be framed for modern technologies such as nanotechnologies and earthworm assisted technologies for the remediation of agrochemical pollution.

In India, the Govt. of Sikkim has turned their agriculture organic by reducing the subsidy on fertilizers and pesticides by 10% every year. Thus, the increasing rate of fertilizers and pesticides leads to lesser use. The state has also banned the import of chemicals and fertilizers from outside states, intending to discourage farmers from

using the chemicals. Again, to reduce the use of chemicals, the government has implemented several alternative strategies, including the use of vermicompost made in vermin hatcheries, biofertilizer, seed processing units, government farms, rural compost pits, organic manure, effective microorganism (EM) technology, integrated pest management, and the establishment of organic farming schools (Kumar et al. 2018).

4 Conclusion and Future Recommendations

Extensive and unjustifiable application of agrochemicals in agricultural/nonagricultural settings to control a diverse range of pests hinders virtually every aspect of the ecosystem, including groundwater, soil, and human health. Homeowners ignore pesticide doses while spraying pesticides. In addition, the indiscriminate use of pesticides in urban environments (parks, lawns, pest control, drainage systems, pathways, etc.) causes runoff during storms or rainfall into urban waterways contaminating both surface water and groundwater. These residues enter the human body through dermal contact, inhalation, ingestion, or eye exposure and may result in various life-threatening diseases in humans as well as animals. Therefore, sustainable agricultural practices such as integrated management of nutrients and diseases are important to achieve a contamination-free environment, healthy food products, and potable drinking water. Emphasis should be given on the following:

- Formulation of less persistent, biodegradable pesticides
- Organic agricultural practices
- Implementation of laws to regulate the production, marketing, and use of pesticides and chemical fertilizers
- Awareness among the farmers and common people on agrochemical uses and its consequences

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